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C. Mazeau, L. Beylat, Patrice Longère, P. Louvigné. On the Quantitative Evaluation of Adiabatic Shear Banding Sensitivity of Various Titanium Alloys. EURODYMAT 1997 - 5th International Conference on Mechanical and Physical Behaviour of Materials under Dynamic Loading, Aug 1997, Toledo, Spain. pp.C3-429-C3-434, 10.1051/jp4:1997374 . jpa-00255531

HAL Id: jpa-00255531

<https://hal.science/jpa-00255531>

Submitted on 4 Feb 2008

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On the Quantitative Evaluation of Adiabatic Shear Banding Sensitivity of Various Titanium Alloys

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ABSTRACT

Titanium alloys exhibit attractive ballistic performances due to their low density and their high mechanical properties. They are unfortunately very sensitive to adiabatic shear localization. This study aims to determine an empirical parameter which allows to characterise the sensitivity to the adiabatic shear banding of different grades of titanium alloys. Dynamic punching tests by split Hopkinson pressure bar are performed on disc shaped specimen to obtain shear bands. This article deals with the possibility to size different materials according to their sensitivity to adiabatic shear on a defined scale with a such simple test.

RESUME

Alliant hautes performances mécaniques et faible densité, les alliages de titane semblent être de bons candidats pour des applications de blindage. Néanmoins, ils sont très sensibles au cisaillement adiabatique, mode de ruine très fréquemment rencontré lors de la perforation d'une cible. L'objet de cette étude est de déterminer un paramètre empirique capable d'identifier la sensibilité au cisaillement adiabatique d'alliages de titane. Des tests de poinçonnage dynamique par barres d'Hopkinson, permettant d'obtenir des bandes de cisaillement sur des disques, sont effectués. La perspective qu'offre un tel test d'établir un classement des différents matériaux sur une échelle de sensibilité est discutée.

1- INTRODUCTION

Adiabatic shear banding has been clearly identified as an important mode of deformation at high strain rates [1, 2, 3]. Then it plays an important role during armour perforation [4, 5]. The thermomechanical environment necessary to form this plastic instability is now established [1]. Adiabatic Shear Band (ASB) has been defined as a stress localization phenomenon generally caused by a plastic instability causing by thermal softening during adiabatic or quasi-adiabatic deformation.

The list of the physical and mechanical factors which have an influence on this process is now also quite exhaustive [1, 6]. Moreover, numerous studies in theoretical analysis [3, 7] and numerical simulation have been achieved in order to define a threshold criterion of the instability initiation. The difficulty of these last studies remains in the lack of experimental data (temperature range...) of this process, eventhough some improvements are realised in this domain [8, 9]. More particularly, during the last decade, the knowledge of the microstructure in the ASB, was greatly improved by a lot of post-mortem examinations, especially by transmission electron microscopy [2, 10, 11 & 12]. Then the exact physical phenomenon is not still clearly understood.

Then many criterions were proposed to predict the Adiabatic Shear Banding Sensitivity (ASBS) and initiation. These criterions are difficult to use, because they need the experimental determination of several mechanical and physical parameters. Moreover they do not often lead to the same conclusions when these models are utilised to compare different materials because of the differences between the criterions [7].

This study aims to propose an empirical parameter taking into account an experimental average value of the localization energy. Afterwards this parameter would be very useful to size titanium alloys in according to ASBS, thus it allows the best choice of a material for ballistic application.

Several grades of titanium alloys, which have different chemical compositions and different initial microstructures, are investigated. The mechanical and physical properties of the different grades are firstly determined in order to use a maximal shear stress criterion similar to Culver's one [1]. On the other hand dynamic punching tests are performed on disc shaped specimens. The different damages induced in the specimen are determined by an optical microscopic examination. Experimental data from dynamic punching test are analysed in order to access to the disc loading and indenter displacement histories. Information allows to calculate an average value of the localization energy. The possibility to establish a size order of material according to the ASBS with such a simple test is finally developed.

2- MATERIALS

One commercial purity titanium (Ti 40) and three titanium alloys (one Ti 20%V 4.5%Al; two Ti 6%Al 4%V; and three Ti 6%Al 4%Zr 3%Mo 2%Cr 2%Sn 1%Fe) are studied. They have different microstructures which lead to different mechanical properties.

2.1- Microstructures

The microstructures of the different grades of titanium are given in the table I and three examples of these different microstructures are presented in the figure 1.

Table I : microstructures of the different grades of titanium

materials	microstructures
Ti 40	equiaxed α [13]grains with mean grain size about 45 μm . (fig.1.a)
Ti 20V 4.5Al	equiaxed β [13] grains with mean grain size about 220 μm .
A/Ti 6Al 4V	equiaxed α grains in a β matrix. The mean α grain size is about 10 μm . (fig.1.b)
B/Ti 6Al 4V	equiaxed α grains in a $\alpha\beta$ matrix. The mean α grain size is about 10 μm .
A/Ti 6Al 4Zr 3Mo 2Cr 2Sn 1Fe	bimodal structure with α phase and β phase [13]. The mean α grain size is about 4 μm ; the α platelet diameter is about 0.70 μm and its length is about 4 μm . (fig1.c)
B/Ti 6Al 4Zr 3Mo 2Cr 2Sn 1Fe	bimodal structure with αp , αs phases and β phase [13]. The mean α grain size is about 4 μm ; the α platelet diameter is about 0.60 μm and its length is about 4 μm .
C/Ti 6Al 4Zr 3Mo 2Cr 2Sn 1Fe	lamellar structure with αp , αs phases and β phase [13].

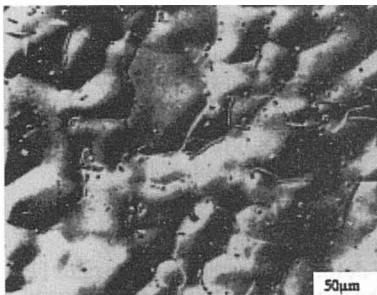


fig. 1.a) Ti 40
equiaxed α grains

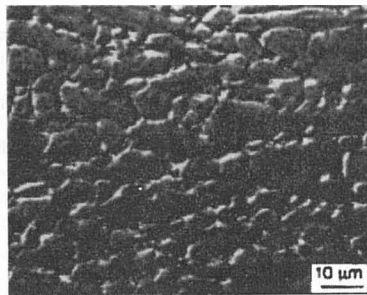


fig. 1.b) A/Ti 6Al 4V
equiaxed α grains in a β matrix

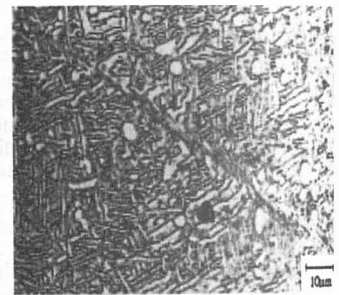


fig. 1.c) A/Ti 6Al 4Zr 3Mo 2Cr 2Sn 1Fe
bimodal structure with two phases

figure 1 : optical micrographs showing different initial microstructures.

2.2- Thermal and mechanical properties

The specific heat (C_p), which is measured by differential calorimetry, is presented in the table II.

The thermal conductivity (K), which is determined from the equation $K = a.p.C_p$ where a is the thermal diffusivity which is measured by the method of modulated incident laserbeam , is presented in the table II.

The mechanical properties are determined for each grade of titanium. Tensile and compressive tests are realised at low and high strain rate (respectively 10^{-3} s^{-1} and 10^3 s^{-1}) at room temperature.

The quasi-static yield stress ($R_{p0.2}$) and the total elongation ($A\%$) are given in the table II.

Table II : thermal properties and static tensile characteristics

materials	density ρ (kg/m ³)	specific heat C_p (J/kg.K)	thermal conductivity K (W/m.K)	$R_{p0.2}$ (MPa)	A (%)
Ti 40	4560	510±50	19	280	≥ 20
Ti 20V 4.5Al	4640	550±10	6.8	587 ±3	26.4
A/Ti 6Al 4V	4460	590±20	8.2	837 ± 6	16
B/Ti 6Al 4V	4460	540±20	7.5	910 ± 3	15
A/Ti 6Al 4Zr 3Mo 2Cr 2Sn 1Fe	4720	500±10	6.3	1022 ± 15	13
B/Ti 6Al 4Zr 3Mo 2Cr 2Sn 1Fe	4720	520±25	6.3	1210 ± 10	9.3
C/Ti 6Al 4Zr 3Mo 2Cr 2Sn 1Fe	4720	520±10	6.7	1095 ± 13	4.7

The addition of chemical element as Al and so on provokes an important decrease of the thermal conductivity, which is already low for titanium.

The increase of the yield stress ($R_{p0.2}$) provokes a decrease of the total elongation ($A\%$)

2.3. Behaviour model and instability criterion

The Johnson-Cook power-law is used in order to describe materials behaviour in compression :

$$\sigma = (\sigma_0 + k \cdot \epsilon^n) \cdot (1 + c \cdot \ln \dot{\epsilon}^*) \cdot (1 - T^{*m}) \quad \text{where} \quad T^* = \frac{T - T_{\text{room}}}{T_{\text{melt}} - T_{\text{room}}} \quad \text{and} \quad \dot{\epsilon}^* = \frac{\dot{\epsilon}}{\dot{\epsilon}_u} \quad (1)$$

The different parameters calculated from this law are shown in the table III.

The condition of adiabatic shear band initiation is usually given by a critical plastic strain criterion. In order to predict the critical instability strain, a modified form of Johnson-Cook constitutive model is used (2). A similar analysis to Lindholm-Johnson's one [1] leads to (3).

$$\sigma = (\sigma_0 + k \cdot \epsilon^n) \cdot (1 + c \cdot \ln \dot{\epsilon}^*) \cdot (1 - b \cdot T) \quad \epsilon_i = \frac{n \cdot \rho \cdot C_p}{b \cdot \beta \cdot (\sigma_0 + k)} - \frac{\sigma_0}{k} \cdot \epsilon_i^{1-n} \quad (2) \text{ and } (3)$$

The "b" parameter and the critical instability strain are calculated and are presented in the table III.

Table III : longitudinal (L) and short transverse (ST) Johnson-Cook power-law parameters for $0 < \epsilon < 0.2$ and $10^{-3} < \dot{\epsilon} < 10^3 \text{ s}^{-1}$

materials	direction	σ_0 (MPa)	k (MPa)	n	c	m	b	ϵ_i (%)
Ti 40	L	380	2000	0.9	10^{-2}	1.8	0	∞
Ti 20V 4.5Al	L	815	620	0.5	$3.7 \cdot 10^{-2}$	0.5	2.10^{-4}	9.5
	ST	840	670	0.45	$3.9 \cdot 10^{-2}$	0.45	2.510^{-4}	6.5
A/Ti 6Al 4V	L	870	990	0.25	$1.1 \cdot 10^{-2}$	1	5.10^{-4}	37
	ST	930	990	0.54	$1.5 \cdot 10^{-2}$	1	7.10^{-4}	50
B/Ti 6Al 4V	L	1048	950	0.2	$1.15 \cdot 10^{-2}$	0.8	8.10^{-4}	12
	ST	1055	760	0.32	$1.5 \cdot 10^{-2}$	0.9	7.10^{-4}	20
A/Ti 6Al 4Zr 3Mo 2Cr 2Sn 1Fe	L	1115	990	0.34	$1.7 \cdot 10^{-2}$	0.65	$1.6 \cdot 10^{-3}$	7
	ST	1190	990	0.5	$1.55 \cdot 10^{-2}$	0.6	$1.7 \cdot 10^{-3}$	6
B/Ti 6Al 4Zr 3Mo 2Cr 2Sn 1Fe	L	1205	990	0.34	$1.5 \cdot 10^{-2}$	0.7	$1.1 \cdot 10^{-3}$	11
	ST	1180	910	0.4	$1.1 \cdot 10^{-2}$	0.7	10^{-3}	14
C/Ti 6Al 4Zr 3Mo 2Cr 2Sn 1Fe	L	1130	970	0.36	$1.32 \cdot 10^{-2}$	0.7	10^{-3}	13.5
	ST	1150	830	0.34	$1.25 \cdot 10^{-2}$	0.75	10^{-3}	12

In the investigated range of strain and strain rate, Ti 40 is very low-sensitive to the thermal softening and very high-sensitive to the strain hardening. Ti20V4,5Al is very sensitive to the thermal softening and to the strain rate. Ti6Al4V and Ti6Al4Zr3Mo2Cr2Sn1Fe alloys have the same sensitivity to the strain hardening and to the strain rate.

3- EXPERIMENTAL PROCEDURE

The punching test set-up used with the split Hopkinson pressure bar (SHPB) was designed at the laboratory by B. Deltort [8] to create shear bands with a perfect control of their length. Its principle is quite similar to Chou's set up [14]. Disc shaped specimens with 26 mm diameter and 2 mm thickness are tested. An advantage of this geometry is the absence of geometric defects on the faces which could be created during the machining. Such defects could induced the ASB appearance.

3.1-Experiment

The punching test set up used in this work is drawn in fig.3. It is inserted between the SHPB, the indenter is located at the end of the input bar and the backup ring at the end of the output bar. A projectile impacts with a controlled velocity the input bar and produces an incident stress wave inside the input bar. This finite wave travels through the input bar and when it meets the punching test device, one part is transmitted to the output bar and the other part is reflected inside the input bar. Numerical simulation with ABAQUS 2D code in explicit version has shown that a monodimensionnal analysis of the test could be utilised to calculate the shear stress (τ) and the penetration depth (u) in a first approximation.

$$\tau = \frac{S_{\text{bar}}}{S_{\text{sheared area}}} \cdot \sigma_T = \frac{D_{\text{bar}}^2}{4 \cdot D_{\text{indenter}} \cdot d_{\text{disc}}} \cdot \sigma_T \quad (4)$$

$$u = -\frac{2 \cdot C_{\text{bar}}}{E_{\text{bar}}} \cdot \int_0^t \sigma_R \cdot d\tau - \frac{\sigma_T}{E_{\text{indenter}}} \cdot d_{\text{indenter}} \quad (5)$$

where D_i is the diameter, d_i is the thickness, C_i is the elastic waves celerity and E_i is the Young modulus of i -element, σ_R and σ_T are the reflected and transmitted stresses inside the bars.
 The shear stress-penetration depth curves for Ti 40 and Ti 20V 4.5Al are represented in figure 4.

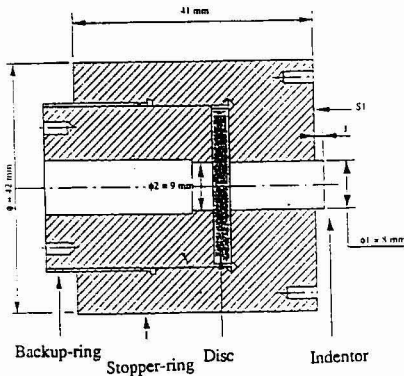


fig. 3 : Punching test device

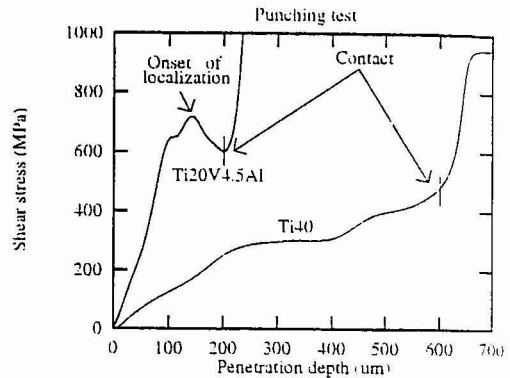


fig. 4 : shear stress versus penetration depth

The figure 4 shows that both materials give different answers in the same initial experimental conditions (specimen geometry and projectile impact velocity) : the shear stress of Ti40 answer is monotonic increasing, whereas the Ti20V4.5Al shear stress increases, seems to reach a maximal value, and then decreases. It is assumed that this maximal shear stress value points out the onset of localization. A similar behaviour is also observed on Ti6Al4V and Ti6Al4Zr3Mo2Cr2Sn1Fe. The last increase of the intensity of the shear stress is cause by the contact between the input bar and the device.

If the $\tau(u)$ curve presents a maximal value of intensity, an average value of localization energy can be expressed by :

$$U_{loc} = \int F \cdot du = S_{sheared\ area} \cdot \int_0^{u(\tau_{max})} \tau \cdot du \tag{6}$$

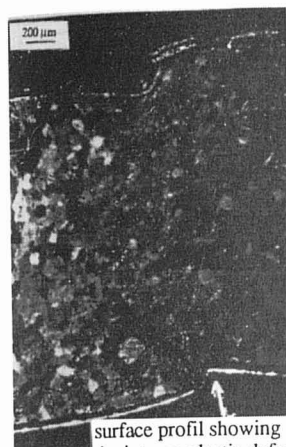
3.2- Results

The maximal shear stress and the localization energy values, which are determined with this punching test, are presented in the table IV.

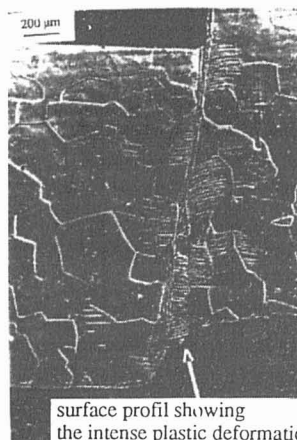
table IV : maximal shear stress (MPa) and localization mean energy (J)

materials	maximal shear stress (MPa)	localization energy (J) U_{loc}	tendency
Ti 40	X	X	1
Ti 20V 4,5Al	715	2.97	2
A/Ti 6Al 4V	993	2.86	3
B/Ti 6Al 4V	832	2.24	4
A/Ti 6Al 4Zr 3Mo 2Cr 2Sn 1Fe	717	1.88	7
B/Ti 6Al 4Zr 3Mo 2Cr 2Sn 1Fe	705	1.74	6
C/Ti 6Al 4Zr 3Mo 2Cr 2Sn 1Fe	777	1.91	5

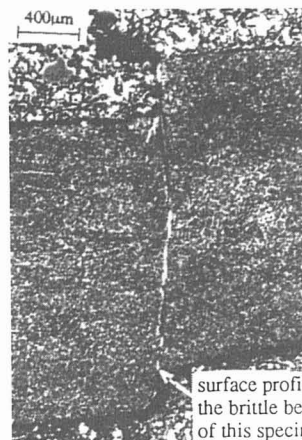
After these tests, the discs are sectioned to be observed by optical microscope. The figure 9 shows very different examples of deformation area in different grades of titanium.



surface profil showing
the intense plastic deformation
fig.9.a : Ti 40 - intense plastic
deformation evidenced without shear band



surface profil showing
the intense plastic deformation
fig.9.b : Ti 20V 4,5Al - intense plastic
deformation with shear band



surface profil showing
the brittle behaviour
of this specimen
fig.9.c : A/Ti 6Al 4Zr 3Mo 2Cr 2Sn 1Fe
- shear band without drastic homogenous
plastic deformation

The whole titanium alloys present shear band except for the Ti 40 (figure 9.a), the shear stress-penetration depth curves present maximal shear stress values for all the titanium alloys and not for the commercial purity titanium. It is important to notice that Meyer [2] created in commercial purity titanium shear band. Then the mechanical interpretation agrees with microscopic examinations. Cracks in the shear band are always evidenced in titanium alloys. An intense plastic deformation is observed on several grades. It could be evidenced by the final shape of the back side (figure 9) and plastic defects like twins (figure 9.a).

From these results, it is possible to establish an ASB tendency (table IV), where Ti 40 is the least sensitive and A/Ti 6Al 4Zr 3Mo 2Cr 2Sn 1Fe is the most sensitive. The size order between the three Ti 6Al 4Zr 3Mo 2Cr 2Sn 1Fe alloys is difficult to do at the present time.

4- CONCLUSION

As far as ballistic applications are concerned, it seems important that target materials spend the greatest energy by intense plastic deformation before localizing with adiabatic shear banding. Indeed this phenomenon often conduces to the catastrophic failure of the target material.

Simple punching tests are performed on disc shaped specimens in this study. This test allows to access to the mechanical behaviour of the material through a shear stress - penetration depth curve. If there is the appearance of shear band this curve exhibits a maximum (τ_{max}). This maximal shear stress is plotted versus the tendency which is obtained by post-mortem examination. The critical instability strain (ϵ_i), which is based on the same assumption (maximal shear stress) is also plotted in this figure.

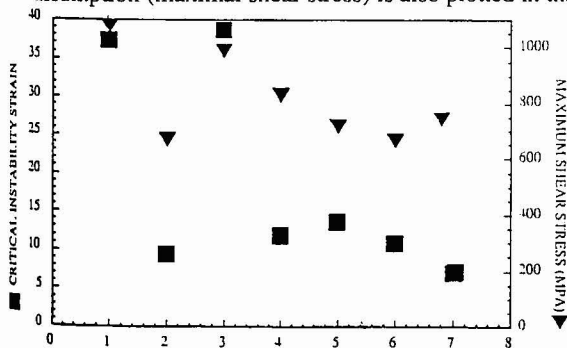


fig.10. : τ_{max} and ϵ_i versus the size order obtained by post-mortem examination

The maximal shear stress and the critical instability strain evolutions are quite similar and do not follow the size order tendency. The critical instability strain is not taking into account all the necessary parameters. This parameter is known as insufficient to predict the adiabatic shear banding appearance [6].

In order to take into account the homogenous plastic deformation, a localization energy value (U_{loc}) is calculated from the maximal shear stress value.

This parameter is plotted versus the classification tendency in the figure 11.

It seems that materials size order which is defined with the localization energy is close to the post-mortem examination one. Thus U_{loc} seems to be the best parameter to consider. In order to confirm furthermore this parameter choice, numerical simulation will allow to obtain a better understanding between experimental data and material answer. The influence of the loading time will also investigate. These researches would allow to confirm our materials size order. Thus the influence of the materials properties (chemical composition, initial microstructure, yield stress...) could be more particularly explained.

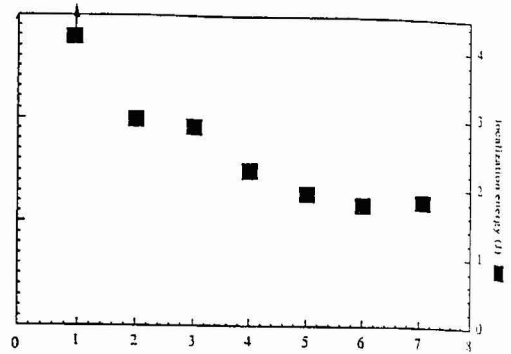


fig.11 : U_{loc} and $Rp0,2$ versus the size order obtained by post-mortem examination

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ACKNOWLEDGMENTS

The authors are grateful to Mrs Porcher and Mr Bégué for their technical assistances, and Mr Taladriz for his help in english.